SEESE

# Investigation of the Aluminum Cell: the Rectifier

Electrical Engineering

M. S.

1913

# INVESTIGATION OF THE ALUMINUM CELL: THE RECTIFIER

BY

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B. S. University of Illinois, 1912

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THESIS

Submitted in Partial Fulfillment of the Requirements for the

Degree of

MASTER OF SCIENCE

IN ELECTRICAL ENGINEERING

IN

THE GRADUATE SCHOOL

OF THE

UNIVERSITY OF ILLINOIS

1913

UNIVERSITY OF ILLINOIS

THE GRADUATE SCHOOL

May 31 1913

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Robert St. Clair Seese

ENTITLED Investigation of the Aluminum Cell: The Rectifier.

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Master of Science in Electrical Engineering

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Chap.

# INTRODUCTION.

In the thesis for the bachelor's degree, the general characteristics of aluminium cells were studied, and a few applications of the cell to commercial work described. In the present work, the important "valve action" of the cell will be more thoroughly investigated, in connection with the application of the cell to the rectification of alternating current.

It is doubtful whether the aluminium rectifier will ever be available for large industrial installations. The excessive cost of materials, and the great amount of care required where good results can be expected, are factors which may never be eliminated. The possibilities of the small cell, however, are great. In the latter part of this paper special attention is given to the small cell, and several examples are cited which emphasize its usefulness in certain lines of work.

Although several European scientists have contributed to the small store of knowledge of the cell, it is impossible at present to say if the aluminium rectifier is or is not practicable, because there are many conditions under which it may operate, and of these only a few have been investigated. Until the real nature of the phenomenon is thoroughly understood, no satisfactory conclusion can be reached.

# CHAPTER ONE.

## Thickness of the Gas Film as Indicated by the Electrostatic Capacity.

It is generally accepted that the "valve action" of an aluminium cell is due to a thin oxide or hydroxide film on the aluminium electrode, overlaid by a thin gas film. To which of these films may we attribute the valve action, or are they both necessary? It may be possible, even desirable, to remove one of the films, or to change their characteristics, in order to increase the effect. This is the first problem dealt with in this investigation.

An aluminium cell is also a condenser, the film forming the dielectric, and the electrode and electrolyte the plates. Fig.1 shows the variation of capacity with impressed voltage[*]. Other factors remaining constant, it is seen from the curve that the thickness of film increases with the voltage, in order to decrease the capacity in the manner shown.

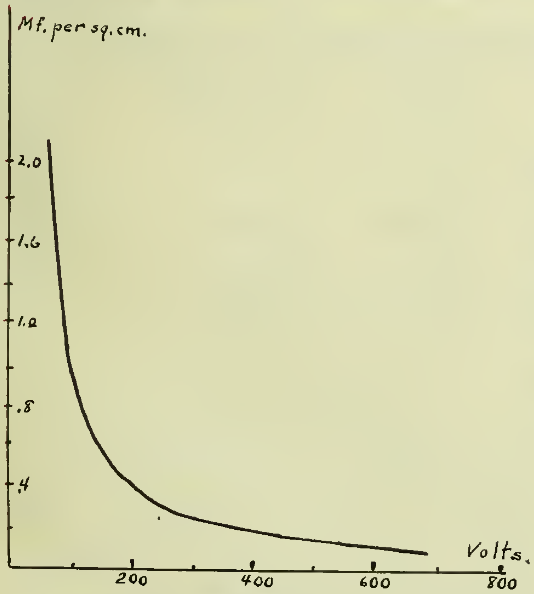

Fig. 1. Capacity of Cell[*].

Since the oxide film has been shown by Dr. Schulze[†] and others to be exceedingly thin and sensibly constant, we deduce at once that the hydrogen film causes this enormous change in the capacity, and hence is the important factor in all phenomena connected with the cell. An exception to this statement exists when the cell has had

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[*] Electrochem. and Met. Ind., Vol. VII, P. 216.

[†] From tests in the Reichsanstalt, 1909.

no potential applied to it for a considerable time, so that the hydrogen film has been entirely dissolved, leaving only the oxide film. This condition, however, does not apply to rectifying cells and will not be considered. It is mentioned somewhat ambiguously in a paper on Lightning Arresters, in the General Electric Review, Vol. XVI, P. 36.

Now for a plate condenser the capacity is

$$C = \frac{k \cdot A}{4 \cdot t \cdot 9 \cdot 10^5},$$ where A is the area of one plate, in sq. cm., k the specific inductive capacity of the dielectric, ( in this case hydrogen,) and t the thickness of the dielectric in cm. For a condenser of unit area, the thickness is therefore

$$t = \frac{8.8 \times 10^{-8}}{C}.$$

Roughly, then, the thickness of film may be calculated from the data used to plot the curve in Table I. The ratio t/E shows

Table I. Calculated Thickness of the Gas Film.

| Cap. m.f. | Volts | t, cm. | Ratio, t/E |
|---|---|---|---|
| .85 | 100 | $.0103 \times 10^{-5}$ | 097 |
| .38 | 200 | $.0231 \times 10^{-5}$ | 115 |
| .25 | 300 | $.0352 \times 10^{-5}$ | 117 |

that for wide changes in voltage, the thickness of film increases almost in proportion to the voltage. Near the limiting voltage at which the film breaks down, the calculated values of t/E increase more rapidly, due no doubt to the puncturing of the film.

The foregoing calculation is based on the assumption

that the oxide film is too thin to have an appreciable effect on the electrostatic capacity. The reasons for this assumption have been given in the preceding paragraphs. The calculation of the thickness of film applies only where the current density on the electrode is small, since with high current densities there is a violent gassing on the electrode which causes the film to be very unevenly distributed.

## Production and Duration of Gas Film.

In the simplest aluminium cell, the electrolyte forms one terminal and the electrode the other. At the instant of closing the circuit on a new cell, the current which tends to flow from electrolyte to electrode establishes a film of hydrogen on the electrode, part of which is continuously thrown off by electrolytic action as long as the circuit remains closed. When the circuit is broken, a part of the hydrogen film remains on the electrode, and under favorable conditions covers it uniformly. For a large potential difference between terminals of the cell, the evolution of gas is rapid, and the gas rises from the plate in bubbles. So long as the current is passing, therefore, the film is not formed, or is at least very imperfectly distributed. For small potential differences the production of gas is small, and the film is more nearly perfect. If the existing potential is slowly decreased, the film becomes more and more uniform and perfect, until the voltage reaches zero, when the film attains its minimum thickness and maximum uniformity of distribution. Obviously, if the film were now perfect, there could be no current thru the cell when the polarity was reversed. There is, however, a small

amount of leakage, showing that even with the greatest care in lowering the voltage, the film has some imperfections.

Since the problem with all aluminium cells is to reduce the leakage for reverse current to a minimum, the production of a good film by the "positive current" is imperative. In the case of alternating current, it is possible to do this in two ways: first, by employing low frequencies; second, by using a wave of E.M.F. which is flat during the latter part of the half cycle. In either method, the rate of change of voltage is reduced, thus allowing the film time to establish itself uniformly before the polarity is reversed, by the beginning of the next half cycle. Table II shows the effect of lowering the frequency in a circuit containing an aluminium rectifier. Since all other factors were kept constant, the efficiency of the rectifier was dependent only on the condition of the film. The increase of efficiency with decrease of frequency is clearly shown, since the data is compiled from the results of five separate tests.

Table II.

Effect of Frequency on Film.

| Cycles | E | $W_{ac}$ | $W_{dc}$ | Eff.%. |
|---|---|---|---|---|
| 60 | 162 | 132 | 13.2 | 10 |
| 47.5 | 161 | 132 | 13.2 | 10 |
| 42.5 | 163 | 138 | 15.6 | 11.3 |
| 36 | 161 | 128 | 15.3 | 12 |
| 24 | 161 | 128 | 17.6 | 13.7 |

Fig. 2 shows a wave form of the shape described above, which would add to the efficiency by producing better films. For industrial purposes, however, it would be impracticable to secure such a wave form.

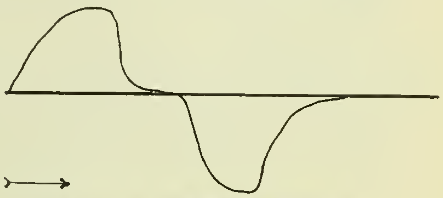


Fig. 2. Wave Form.

The above reasoning does

not hold for all kinds of cells, for with some kinds of electrolytes the effective thickness of film is determined by the maximum voltage, and does not at once decrease with a decrease with a decrease of voltage. This condition is represented by the curve B, Fig. 3, as distinguished from A, in which the film at once falls off. The type of cell following the curve B is adapted for condensers and lightning arresters, where a constant film is wanted. A group of such cells is shown in Fig. 4, which is a lightning arrester designed by the writer for the Clinton (Ia.) Street Railway Co. It is intended to meet unusually severe storm conditions due to the peculiar topography of the country, and is therefore equipped with an electrolyte which gives a remarkably strong and lasting film. ( The curve A is drawn from data on a cell containing electrolyte furnished by the American Battery Co. for small rectifiers, the chemical composition being mentioned later.)

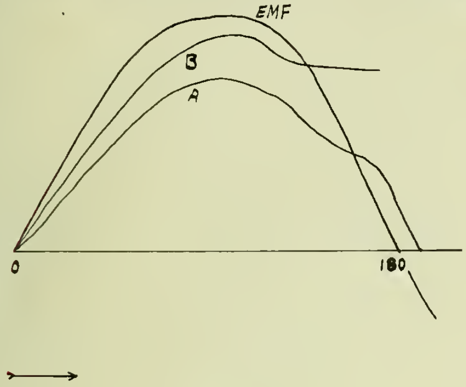
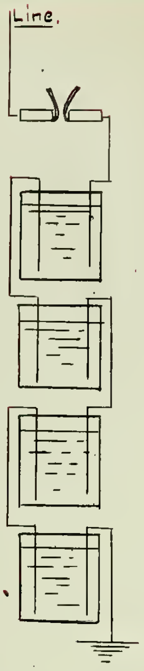
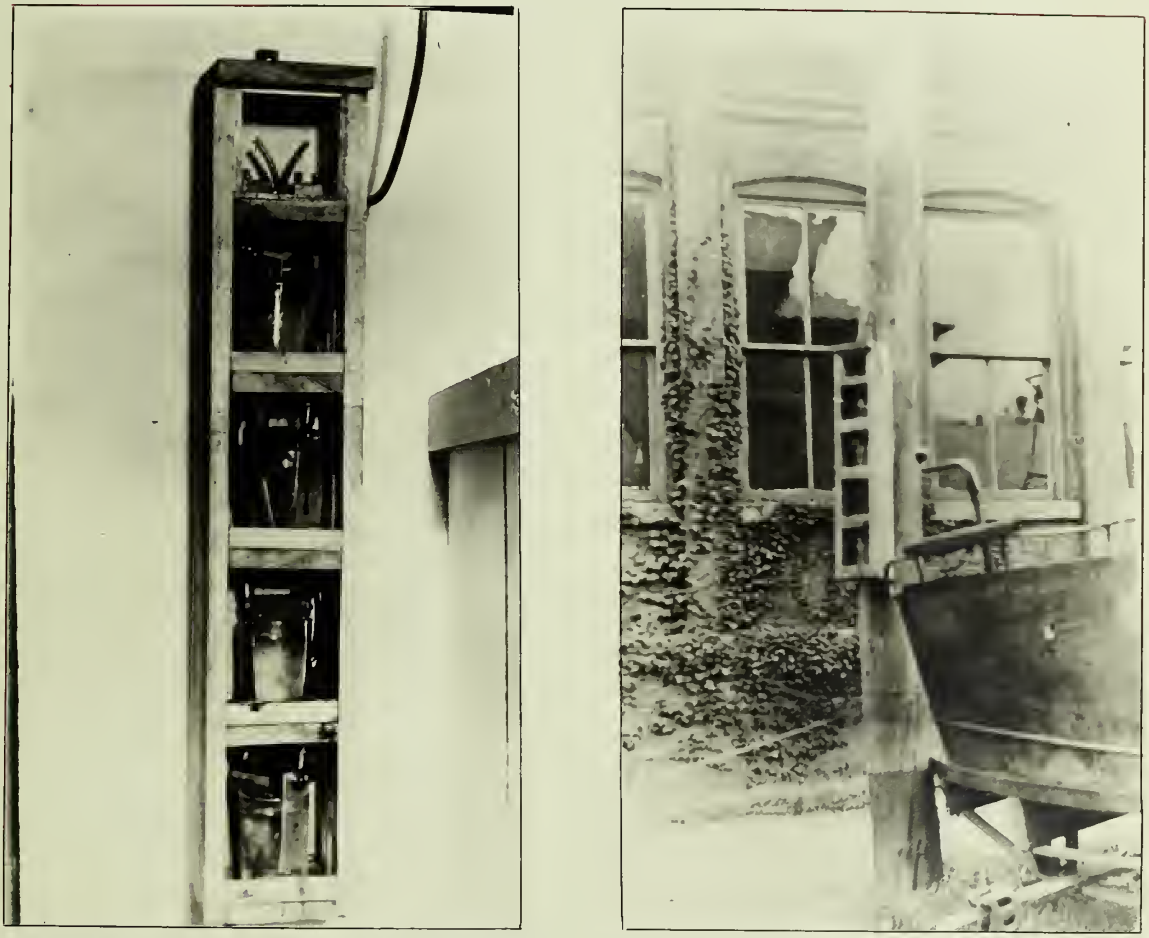


Fig. 3. Film Duration.

There are other factors which must be considered when investigating the properties of the film. The condition and kind of electrolyte, the condition of the electrodes, the temperature of the cell are all important. The best condition is reached when the film may be very quickly formed, or dissolved, at the end of the respective half-cycles. Anything which prevents the rapid formation of the film or hinders its dissolution must therefore be carefully guarded against. The



(a) Wiring diagram of arrester.



(b) Arrester with cover removed. (c) Arrester on pole for test.

Fig. 4. Aluminium lightning arrester for 750 volt trolley, equipped with electrolyte giving especially durable gas film.

effects of temperature changes and foreign material in a cell are well known, and need no further explanation.

### The Film Unit.

So far we have considered only the most simple and fundamental part of the aluminium cell: an aluminium electrode, its film, and the electrolyte immediately surrounding it. We shall for convenience call this portion of the cell a film unit, for some cells have several film units, and in the more complicated cells it is sometimes difficult to distinguish between the actual film unit and the auxiliary parts. We have in the preceding paragraphs endeavored to show that the action of the cell depends entirely on the film unit, and have explained what is now believed to be the true theory of the valve action. We may now study the application of this peculiar property to a complete cell, and to the rectification of alternating current.

As the electrolyte forms one terminal of a unit, it is necessary to provide some means for introducing the current into into it. This is usually done by inserting a lead or iron electrode into the electrolyte, these substances being chosen because they do not react chemically with the alkalies used for electrolyte. It is often convenient to make the containing vessel of one of these metals, as it forms an electrode which almost surrounds the electrolyte and thus reduces the contact resistance. The size or composition of the electrode do not, however, play the least part in the rectifying action.

### Real Nature of the Gas Film.

There has been considerable difference of opinion

regarding the real nature of the gas film on the aluminium electrode. For example, Mr. R. T. Wagner, of the General Electric Company, makes the rather broad statement that the oxide or hydroxide film gives the valve effect, aided by another overlying film composed of oxide and "gases which are apparently in the liquid form." So far as we know, no data has been published which gives good grounds for the belief that the oxide film is the controlling factor in the valve action, or that gases in the liquid form are present. From the primary battery we learn that polarization is caused by the adherence of a gas to the electrode, and there is no difficulty in conceiving myriads of little gas molecules adhering to a roughened plate or electrode, in such close proximity that the electrode is practically insulated from the electrolyte.

From past experience, it seems likely that the oxide film serves as a base upon which the gas film is built, because if it could be sufficiently magnified, the oxide would no doubt appear in a more or less uneven and granular state, to which the gas molecules might readily adhere. There is, however, no further proof that the oxide film acts in this manner, as it has thus far been impossible to eliminate it from the surface of the electrode, to find the action with only a gas film.

The dissolution of the gas film is another theory which is difficuly to reconcile with existing data. There is no reason to believe that the oxide film is broken up in the same manner as the gas film, for every reversal of the current. Since the contact resistance of aluminium with electrolyte in

a cell is always comparatively high regardless of the direction of the current, it seems reasonable to believe that the oxide film only covers a certain percentage of the entire metallic surface, increasing the energy loss of contact resistance, but having no inherent effect on the valve action. This conclusion is strengthened by the results of a test in which electrodes of different shapes and degrees of oxidation were employed. The efficiencies when using them for rectification did not vary greatly, but there was considerable variation in the contact resistance. The following table shows the results.

Table III.

Effect of the Oxide Film on Valve Action and Contact Resistance.

| Kind of electrode | Relative energy loss with D.C. | Relative efficiency, rectifying. |
|---|---|---|
| Smooth cylindrical, sandpapered | 1.00 | 1.00 |
| Same, oxidized, | 1.25 | .95 |
| Same, " and roughly cleaned | 1.18 | .98 |
| Flat rectangular, sandpapered | 1.08 | .97 |
| Same, oxidized, | 1.30 | .95 |
| Same, " and roughly cleaned | 1.25 | .96 |
| Very rough flat, sandpapered | 1.13 | .96 |
| Same, oxidized, | 1.30 | .95 |
| Same, " and roughly cleaned | 1.26 | .95 |

## Energy Loss.

The energy lost in a cell may be separated into three parts:

1. Contact resistance loss at the aluminium, or film unit loss;
2. Chemical energy loss;
3. $I^2R$ loss in the body of the electrolyte;

The first loss is the most serious, and is responsible for the low efficiency of the cell. The reduction of this loss constitutes the most important problem of the aluminium rectifier. At present, it is not very clear just how this loss takes place. The best explanation seems to be that the film at all times covers a very large percentage of the aluminium electrode, and that the current can only pass thru those spots where the film is defective, or is entirely lacking. The enormous reduction in the effective area of the electrode therefore causes a large current density at the spots where the current passes thru, hence the large loss.

The second loss occurs when the electrolyte is decomposed. Although the amounts of energy necessary to decompose the various kinds of electrolyte were not calculated in the preparation of this paper, careful tests with a low reading wattmeter failed to reveal any appreciable loss due to this cause, since the rate of decomposition is for ordinary conditions very low.

The $I^2R$ loss of the electrolyte is practically under control, as by making the electrodes large and the electrolyte concentrated it can be reduced to a very small percentage of the total loss. No special attention was paid to the reduction of this loss in the experimental work. The following table shows the comparative losses, measured with a wattmeter whose

full scale reading was 5 watts.

### Table IV.

### Separation of Energy Losses.

| Test No. | Electrolyte | Film Unit Loss | Chem.Loss | $I^2R$ Loss |
|---|---|---|---|---|
| I | Sod. Bicarb. | 94 % | 0 (?) | 6 % |
| II | " " | 94 | 1/4 | 5 3/4 |
| III | " " | 95 | 0 | 5 |
| I | Ammonium Salts | 93 | 1/2 | 6 1/2 |
| II | " " | 93 | 0 | 7 |
| I | " " (2) | 92 | 1/4 | 7 3/4 |

## Similarity of Aluminium Cell- and Corona Phenomena.

An interesting part of the aluminium cell phenomenon is the character of the voltage-loss curve, which greatly resembles the voltage-loss curve of corona. It is mentioned here not to give the impression that the two phenomena are identical, but merely to show several points of similarity as a matter of interest.

On increasing the voltage on an aluminium cell, the loss gradually increases, up to a certain critical voltage, at which a faint glow appears on the aluminium electrode. On a smooth and uniform electrode, the glow is uniform and extends over the entire electrode, but if there are a number of points or irregularities, the glow is more pronounced at these places. After the critical voltage has been passed, the loss rapidly increases until breakdown occurs.

This is exactly the same chain of events observed when the voltage between high potential terminals is raised

in air. The voltage- loss curve is almost a straight line up to the visual critical voltage, after which the loss increases rapidly until breakdown occurs. Moreover, it is well known that any sharp points or projections increase the corona loss, and the glow attending it.

There have been several theories advanced to explain this peculiar behavior of the cell. The first states that the glow is caused by the "collision of electrons" familiar in the theory of corona; the second, that at the critical voltage, the film begins to be punctured at thousands of places on the electrode, and that the little disruptive sparks cause the glow. The latter is the easier to believe, although it causes the first radical difference in the two phenomena just stated.

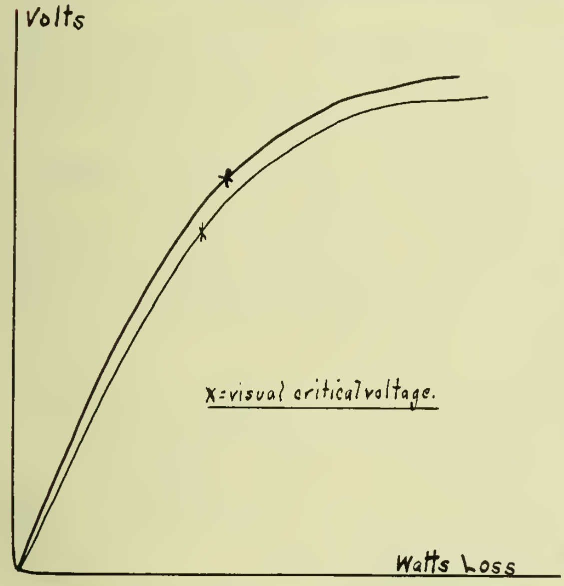


Fig. 5. Voltage-loss Curves.

Fig. 5 shows the two loss-voltage curves and their striking similarity. The corona curve was obtained from a paper by Görges, Weidig, and Jaensch, (Elek. Zeit., Oct. 26, 1912.) The aluminium cell curve was obtained from test data by the writer.

## CHAPTER TWO.

It is desirable to briefly describe the tests made in the preparation of this thesis, in order that the reader may know to what extent they are reliable. It frequently happens that the most careful tests fail to take account of some important factor which the investigator has overlooked, and by merely glancing at tables of data, the reader is unable to judge the extent of the oversight. The data from these tests is included in tables thruout the thesis.

### Film Tests.

In all tests of efficiency, film condition, effect of temperature, frequency, voltage, etc., a standard arrangement of apparatus was used, with the same instruments at all times, (Fig. 6). A thin glass cell of 225 c.c. capacity was used, and all tests not directly concerned with temperature variations were made at 21° Cent. The input of the cell was measured by an alternating current wattmeter, the energy loss of the voltmeter being negligible, as determined by a separate test. The actual d.c. output was measured by voltmeter and ammeter, as the energy loss of the leakage current would have produced an error in the readings, had a wattmeter been used. Corrections were applied to all readings by means of the calibration curves furnished with the instruments. In

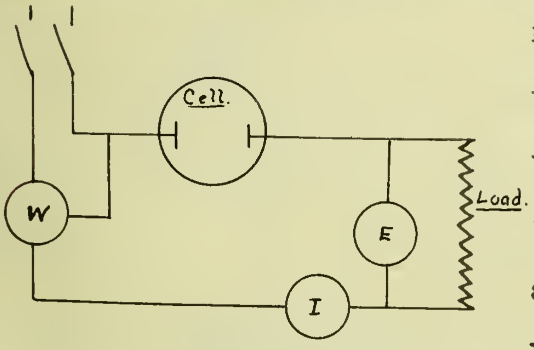


Fig. 6. Film Tests.

tests involving wide variations in frequency, a wattmeter furnished by the General Electric Co. was used, it having been calibrated for a range of from 25 to 133 cycles.

### Energy Loss.

In measuring the energy lost in an aluminium cell, for various conditions, the arrangement shown in Fig. 7 was used. Both direct and alternating current were available by throwing the switch A, so that the effect of alternating current on a film formed by direct current was readily observed. In order that the energy loss might be found for a sufficiently high current density, it was necessary to raise the voltage to a rather high value. For this reason a potential transformer was included in the equipment, and was thrown into the circuit when required by the switch B.

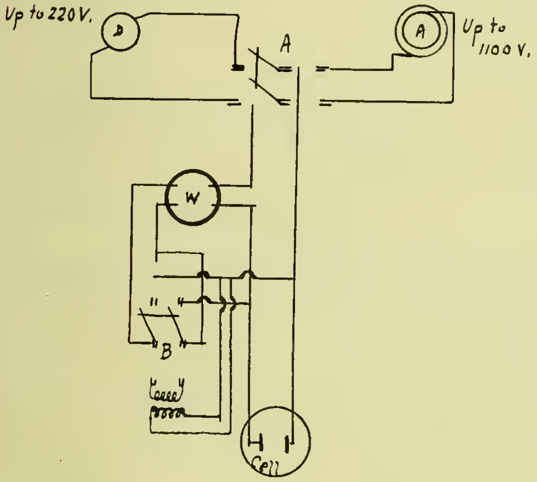


Fig. 7. Energy Loss.

### Separation of Energy Losses.

For studying the division of energy loss in a cell, a number of cells of identical construction were connected in series, (as shown in Fig. 8,) so that the same current flowed thru all. In cell No. 1, containing aluminium electrodes, the loss for alternating current consisted of three parts: film loss, chemical energy loss, and $I^2R$ loss of the electrolyte. In cell No. 2 the film loss was eliminated by replacing the aluminium with lead plates, made large to render the contact resistance

small. In Cell No. 3, pure alternating current was used, and was obtained by operating a double throw switch, so that the the same instruments could be used. In this cell, therefore, the only appreciable loss was that of $I^2R$. No. 3 of course used the same kind of electrodes as No. 2. In this test it was necessary to use a sufficiently high voltage to cause an energy loss great enough to be read with ordinary instruments.

A plug switch was used to throw one wattmeter on any one of the cells, so that any error in the instrument would be the same for all three cells, thus making the ratio of the losses very nearly correct.

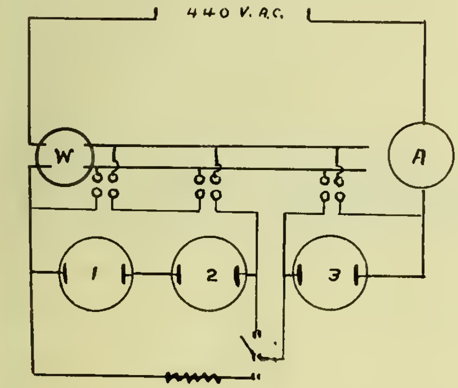


Fig. 8. Separation of Losses.

Effect of Atmospheric Pressure.

The effect of atmospheric pressure on the film was studied by a simple apparatus, a photograph of which is reproduced in Fig. 9. The general wiring diagram is the same as that for the first test mentioned in this chapter. The results checked quite well with those published by Dr. A. P. Carman in the "Physical Review." On account of the great variation due to the use of different electrolytes, no important data was preserved from this test, except a sufficient amount to show that a change of two or three atmospheres above atmospheric pressure did not produce an important change in the valve action, so far as rectification was concerned.

Fig. 9. Pressure Apparatus.

## Tests of Rectifying Sets.

The effect of atmospheric pressure on the film unit was, however, only a subdivision of the study of rectifier sets. Several types of aluminium rectifiers were tested, and in all cases the input and output were measured in the manner described above. In the single phase types at overload, the total current in the rectified circuit greatly exceeded that measured by the D.C. ammeter, on account of the large leakage current. The amount of this total current was found by placing an AC-DC ammeter in series with the other. From the two readings of current, the leakage- and capacity-current was then found, and the result checked by the oscillograph. A detailed explanation of this simple method will be found in the thesis for 1912, on "Investigation of Aluminium Cells."

## Breakdown Tests.

For comparing the films formed by various electrolytes, direct current was used. Two generators in series gave the necessary voltage, which was controlled by varying one of the fields. An ammeter in the circuit indicated the approach of the breakdown point. For establishing the visual critical voltage mentioned in the preceding chapter, the

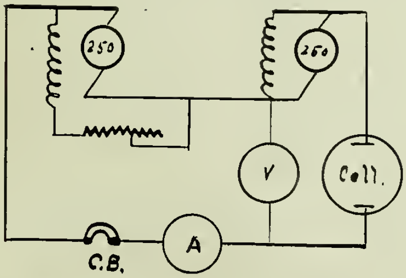


Fig. 10. Breakdown Test.

direct current machines were replaced by an alternator giving a sine wave and a voltage up to 1100.

## CHAPTER THREE.

After understanding thoroughly the limitations imposed by the character of the film loss in an aluminium cell, we may study the ways in which the valve action may be utilized for rectification purposes. It has been stated previously that for large installations where the question of efficiency is all-important, the aluminium cells herein described would not be satisfactory. However, if subsequent improvements are made which will increase the efficiency of the elementary film unit, then it is certain that the types of rectifiers mentioned in this chapter will be well adapted for all purposes requiring the conversion of alternating into direct current. Bearing these facts in mind, we shall now study a few types of rectifier construction.

### Single Phase One Way Cell.

The commonest form of aluminium rectifier, and the only one which has thus far been put on the market, is the "one way" cell shown in Fig. 11, consisting of a simple cell in series with the load and a suitable resistance or reactance. Under favorable conditions, as high as 40% efficiency may be expected from such an apparatus. The manufacturers of the "American" rectifier claim an efficiency of over 60%, but this has not been substantiated by any tests by the writer. With a specially constructed electrode, and electrolyte from the "American" rectifier, the efficiencies for a small one way rectifier were as given in table 5.

With various electrolytes the efficiencies range from

20 to 35%, for various conditions.

The load characteristic of a one way cell shows that for average conditions a current density of about 1/2 ampere per square inch on the aluminium electrode gives the best efficiency and the least leakage. The regulation of a cell built to give this current density at full load is very good; its value when using ammonium electrolytes is about 2%.

Single Phase Two Way Cell.

In order to secure a smooth wave of direct current, the two way cell should be used. This device is not on the market, although Siemens has recently attempted to introduce several types of two way cell, (Elec. World, Vol. 60, P. 368.) The type shown in Fig. 12 is however strictly original, so far as the types constructed by others are concerned. It employs a reactance across the line, which may have variable voltage taps, and is therefore more expensive than the one way rectifier, except in cases where a transformer is used with the one way type, which frequently happens when the ratio of the A.C. and D.C. voltages is to be greatly different from the normal ratio, 0.3175.

Table V. Efficiencies of One Way Cell.

| $W_{ac}$ | $E_{dc}$ | $I_{dc}$ | Eff.% |
|---|---|---|---|
| 69 | 39 | .53 | 30 (I) |
| 60 | 40 | .50 | 33.3 |
| 50 | 35 | .57 | 40 (II) |
| 54 | 35 | .57 | 37 |
| 49.1 | 35 | .58 | 41.5 |
| 50 | 35 | .56 | 39.2 |

The two way rectifier utilizes both lobes of the A.C. wave, and if a small reactance is inserted in the D.C. circuit, a comparatively smooth curve of D.C. voltage is obtained, which

is suitable for operating any kind of direct current apparatus. The regulation of this type is practically the same as that of the one way cell.

The idea that a two way cell is twice as efficient as a one way cell might readily be gained from the first glance at the wiring diagram. Such an idea is, however, erroneous. Disregarding the two way cell for a moment, and returning to the elementary film unit, we find that such a unit may of itself rectify only half-waves, so that in a combination of film units, such as that of a two way cell, the full load capacity is increased, but the efficiency remains the same. There is of course no negative current in the rectified circuit at any time, and this is a distinct advantage in some classes of work; but there are some losses which do not exist in a one way cell: the exciting current loss in the reactance, and the loss caused by the charging- and leakage-current between the two aluminium electrodes. The efficiency may therefore be either greater or less than that of a one way cell, depending on the design.

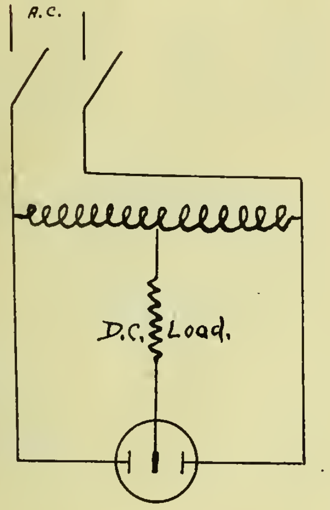


Fig. 12. Two Way Cell.

However, the use of a reactance means a saving in power, and with variable voltage taps a point may be reached where the charging- and leakage-current is greatly reduced, so that a very satisfactory efficiency may be obtained. The following table gives the efficiencies for a two way cell con-

structed by the writer.

Table VI. Data on a Two Way Aluminium Rectifier.

| | Cycles | $W_{ac}$ | $E_{dc}$ | $I_{dc}$ | Eff.%. |
|---|---|---|---|---|---|
| I | 60 | 380 | 25 | 6.08 | 40 |
| II | 60 | 375 | 20 | 6.17 | 33 |
| III | 60 | 350 | 21 | 6.12 | 36.7 |
| I | 25 | 280 | 20 | 5.5 | 39.2 |
| II | 25 | 275 | 20 | 5.45 | 39.6 |
| III | 25 | 292 | 20 | 5.8 | 39.8 |

Reactance loss at 60 cycles, 13w.

Full load, 20V., 5A.

Regulation, 3 %.

Size of cell, cap. 225 c.c.

## Three Phase Cell.

By employing suitable reactances, and a cell having several aluminium electrodes, polyphase rectifiers may be constructed. The D.C. voltage for this kind of rectifier is very smooth, and the reactance in the rectified circuit may in most cases be omitted. The load capacity of the cell is three times that of the one way cell, although the loss per electrode is the same, and so the containing vessel must be enlarged accordingly, in order that the heat may be radiated properly. The reactances may be constructed on one core, as the primary of a three phase transformer, or on three separate cores. The latter method is perhaps better.

Siemens has devised several types of three phase cells, all differing from the above idea. Most of his cells, however, are unsymmetrical; that is, the currents in the three A.C. feeders must from the construction of the cell be different at all times. (This would of course be objectionable only in large rectifiers.) In most of his designs he has used resistances which in commercial work would be objectionable from the standpoint of economy.

It is not desirable to build small three phase recti-

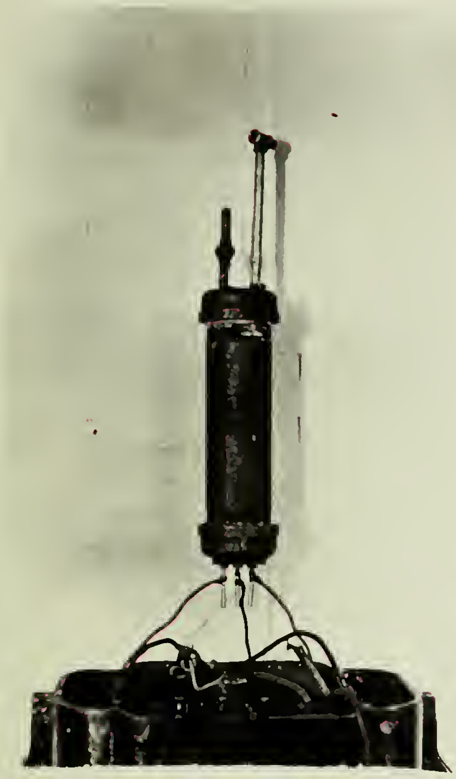


Fig. 13. 3-Phase Type, Aluminium Rectifier.

fiers, as three phase current is seldom available for small installations outside the laboratory. For large rectifiers, however, the three phase type is well worth consideration. If by suitable means the efficiency of a film unit can be raised above 60%, the success of the polyphase rectifier is assured. The following table shows the efficiency of a three phase type, and includes the entire apparatus. The efficiencies are not as high as they would have been had specially constructed reactances been used. Fig. 13 shows the three phase rectifier used in this work. ( The pipes at the top are the terminals of the cooling system, which had been removed when the photograph was taken.

Cooling.

For large rectifiers, the electrolyte must be changed constantly, in order to conduct away the heat. This may be done by having a very large vessel to contain

Fig. 14. Cooling Tanks.

the film units, so that convection currents may automatically cause circulation, or by having a separate cooling tank, thru which the electrolyte may be circulated. In the experiments for this work, two tanks were used, one on each side of the rectifying cell, so that the electrolyte passed thru the cell while being forced from one tank to the other. Circulation was accomplished by compressed air, admitted thru a three way valve, manually operated, which filled and emptied the tanks alternately. In an automatic system the tanks would be replace by a small cooling tower, and a motor-operated pump. The cooling tanks had the advantage for experimental work that the gases formed in the rectifying cell could be drawn off at the valves on top, for examination. Fig. 14 shows the cooling tanks used in the experiments.

Table VII. Efficiency of 3-Phase Aluminium Rectifier.

| Watts$_{ac}$ | Volts$_{dc}$ | Amps.$_{dc}$ | Eff.% |
|---|---|---|---|
| 85 | 68 | .455 | 36.5 |
| 110 | 67 | .58 | 35.5 |
| 142 | 65 | .78 | 36 |
| 170 | 60 | .96 | 35.2 |
| 330 | 60 | 1.93 | 35 |

A.C. Volts 110. cycles, 60.

## Regulators.

The ordinary types of feeder regulators and constant current transformers might readily be applied to any of the above rectifiers, if a source of constant direct current was desired.

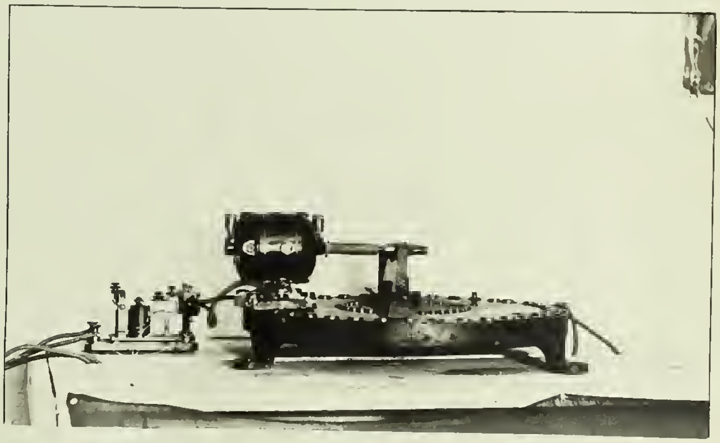


Fig. 15. Automatic Regulator.

Fig. 15 shows a special regulator which could readily be changed from a constant current- to a constant voltage-regulator, and was useful in performing some of the experiments, especially the life tests. A small reversible motor was worm-geared to a field rheostat, and its speed and direction controlled by an auxiliary double-pole relay, shown in the figure. The auxiliary relay was in turn controlled by the main relay, which was a vane type indicating meter whose pointer made or broke a contact at a certain predetermined rise or fall of voltage (or current,) in the circuit.

## Oscillograms.

In order to give an idea of the character of direct current from the different types of rectifiers, oscillograms were taken, and are reproduced on the following page. An explanation of each follows:

A. One Way Cell, normal load. Shows the amount of charging- and leakage current which can ordinarily be expected.

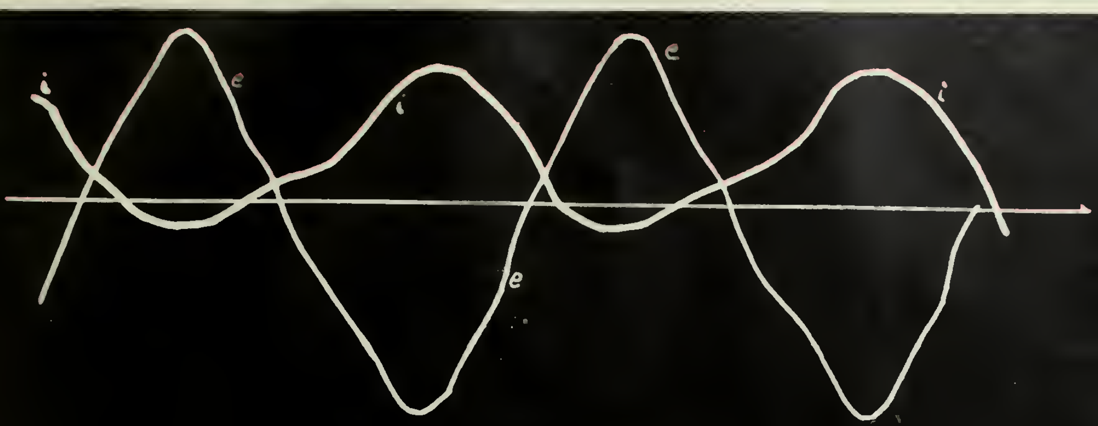
B. Same, overload. Shows enormous increase of leakage, being practically an A. C. wave.

C. Two way cell, without the reactance in the D.C. circuit. The wave would have been improved by using the reactance.

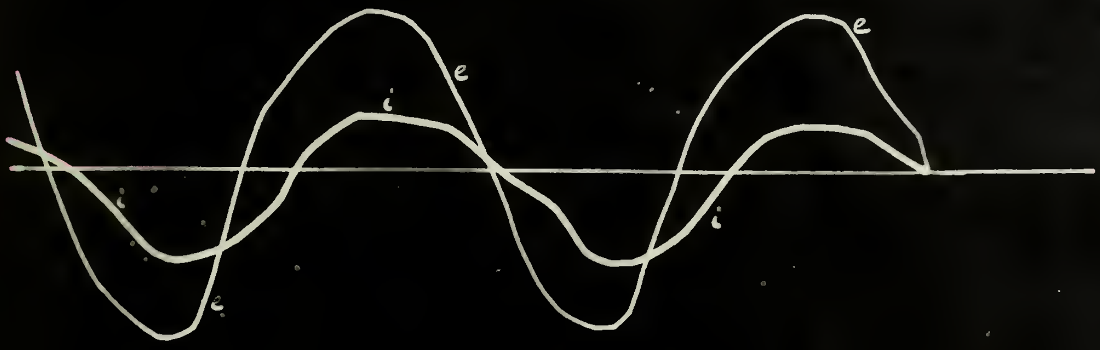
D. Two phase cell, EMF's at 120°. Of no value except to show how a D.C. wave is built up by the addition of displaced A.C. waves.

E. Three phase cell, normal load, no reactance in D.C. circuit.

F. Same, with reactance in the D.C. circuit, showing smoother D.C. EMF obtained by this means.



(A)



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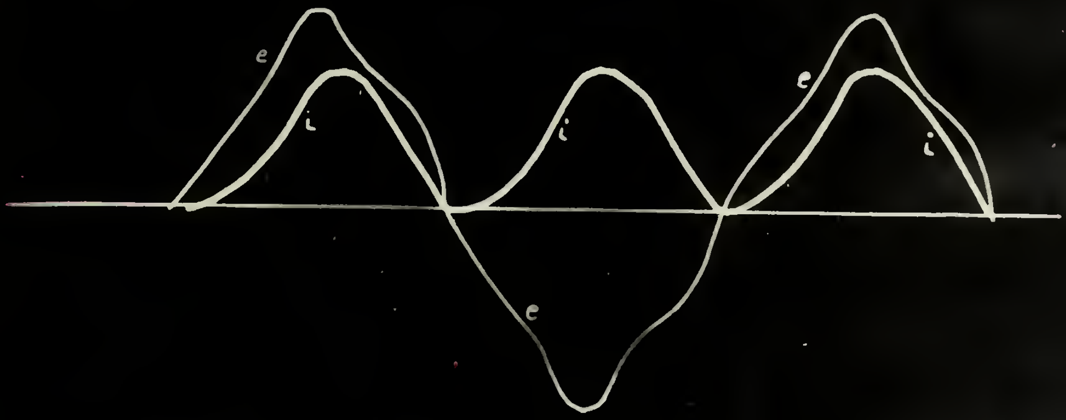

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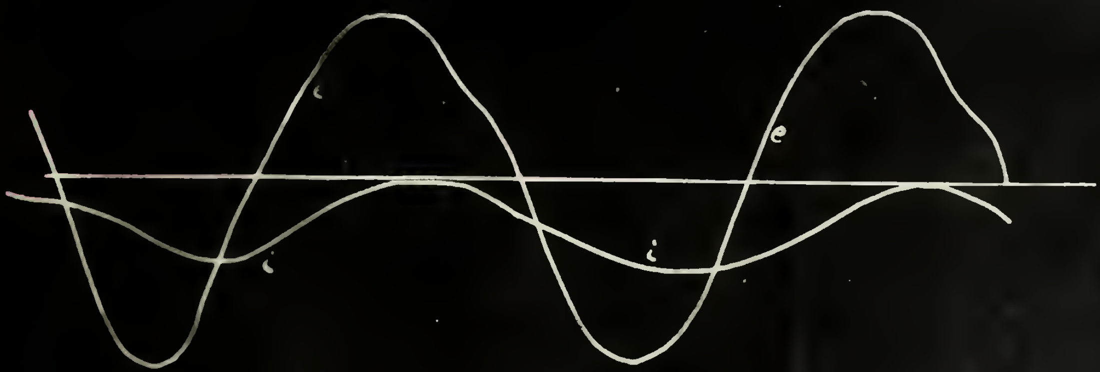

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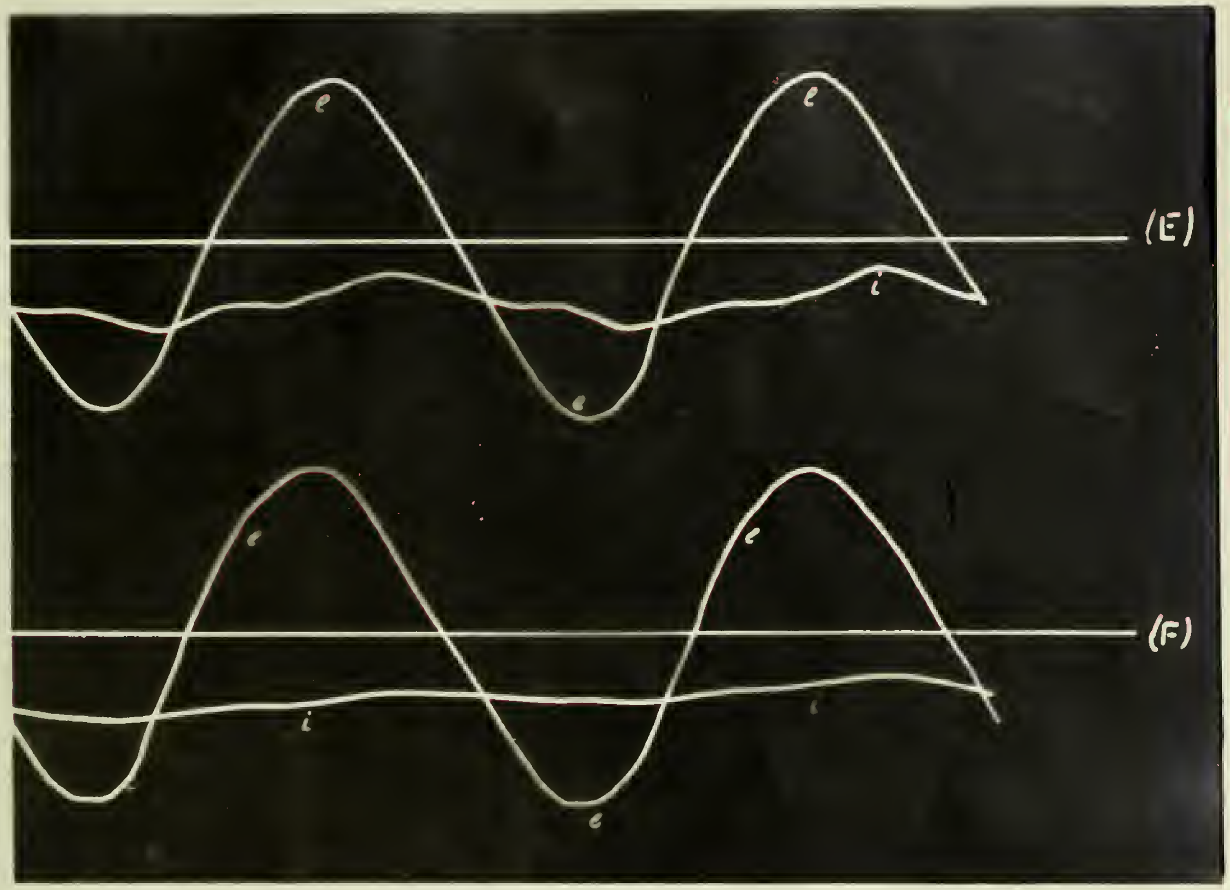
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## CHAPTER FOUR.

### Uses for the Aluminium Rectifier.

The small aluminium rectifier is adapted to a number of different uses, where efficiency is not of prime importance. Storage batteries for gas engine ignition and laboratory use may be charged, motors and induction coils operated, and electrolytic processes carried on by the current from single phase outfits. Telephone exchanges requiring pulsating direct current may economically install and operate a rectifier, thus eliminating the large number of dry cells, or the storage battery usually found in the central office equipment. Costs of material and operation of small rectifiers are given elsewhere in this chapter.

Omitting the question of efficiency, the aluminium rectifier is well suited to a variety of uses. For voltages higher than 110, two cells may be placed in series; for very low voltages a number of cells in parallel, or a single cell having very large electrodes may be used. As stated in the first chapter, the regulation of the cells is good within the limits of efficient operation, and any inconstancy may be eliminated by a suitable type of regulator.

### Commercial Developments.

Several years ago the General Electric Co. placed on the market a one way cell, complete with switchboard panel and regulating device, for charging storage batteries. Due to the low efficiency the rectifier was soon withdrawn, and we have no record of further developments by this company of the rectifying cell, although they have done much toward the

perfection of the aluminium lightning arrester. About one year ago, the American Battery Co. introduced a similar one way cell, intended for charging ignition batteries, for which they claim an actual cell efficiency of 65 %. The "American" rectifier is furnished for 110 volt circuits, in 5 and 10 ampere sizes, with either a lamp bank or transformer, depending on the direct current voltage desired. No data is at present available to show the number of these outfits in operation, or the degree of success attending their use.

Costs.

In order to show approximately the cost of rectifiers, and give some idea of the cost of operation, the following table has been prepared. The figures are based on aluminium at 90¢ per pound, chemicals at wholesale rates, and electrical energy at 10¢ per Kw. Hr. The depreciation of the aluminium and electrolyte were determined by life tests in 1912, and from the data thus obtained, the design of the cells mentioned in the table is such that the life of the electrolyte is 25 hours, that of the electrode 50 hours, at full load. The cells mentioned are self cooled, sufficient electrolyte being used to prevent the cell from overheating.

Costs of material include the profit which manufacturers expect from such apparatus, and are based on the costs of electrodes and containers now on the market for other purposes. The cost of labor in assembling the various parts has been taken as 25¢ per hour, with no provision for profit.

## TABLE VIII.

### Costs of 110 Volt Aluminium Rectifiers up to One Kilowatt.

| Type | Use | Size, Amps. | - - - - Costs of | | | | | | - - - - | Total Cost | Cents/KwHr. | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | A | B | C | D | E | F | G | | Energy | Total |
| 1-way | General | 2 | .35 | 0.00 | 1.00 | .15 | .30 | .50 | .80 | 2.90 | .25 | .27 |
| | | 5 | .50 | | 1.25 | .35 | .75 | .75 | .90 | 4.50 | .25 | .26 |
| | | 10 | .85 | | 1.50 | .70 | 1.50 | 1.00 | 1.00 | 6.55 | .25 | .255 |
| 1-way | Telephone | 5 | .50 | | 1.00 | .35 | .75 | 3.50 | 1.50 | 7.60 | .25 | .26 |
| 2-way | General | | | | | | | | | | | |
| Type NV | | 2 | .35 | 3.00 | 0.00 | .25 | .30 | .75 | 1.10 | 5.75 | .25 | .27 |
| | | 5 | .50 | 5.00 | | .50 | .75 | 1.25 | 1.25 | 9.25 | .25 | .26 |
| | | 10 | .75 | 7.50 | | 1.05 | 1.50 | 1.75 | 1.45 | 14.05 | .25 | .255 |
| Type V | | 2 | .35 | 3.50 | | .25 | .30 | .75 | 1.10 | 6.35 | .23 | .25 |
| | | 5 | .50 | 5.50 | | .50 | .75 | 1.25 | 1.25 | 9.75 | .23 | .24 |
| | | 10 | .75 | 8.00 | | 1.05 | 1.50 | 1.75 | 1.45 | 14.55 | .22 | .23 |

The articles denoted above by letter are: A-container; B-reactance; C-resistance; D-electrode; E-chemical; F-acessories; G-labor.

"Type NV" has no variable voltage taps on the reactance. "Type V" has such taps, by means of which the alternating voltage can be adjusted to give the most efficient results for any one load.

## Electrolytes. Electrodes.

Chemists who have made a study of the reactions taking place in the aluminium cell have recently given out important information, which coincides with the results of the tests for this investigation. It therefore seems well to include them in this chapter, as they have an important bearing on the commercial development of the cell.

It seems that the ammonium salt of an organic acid gives the best results as an electrolyte. Citric acid and phosphoric acid are among the most important, the former, as ammonium citrate, being used to some extent in lightning arresters. As fungus forms readily in such solutions, it is necessary to add a disinfectant, such as phenol. Inorganic salts such as ammonium carbonate, ammonium sulphate, sodium bicarbonate, etc., also give more or less satisfactory results.

In the design of electrodes, purity, smoothness, and reduced current density are important. The best design, where the construction of the cell will permit, is a smooth rod of aluminium, rounded at the end, and surrounded, at least partly, by the lead electrode. A current density of 1/2 ampere per square inch, as mentioned in the preceding chapters, will insure the best working conditions, so far as this requirement is concerned.